Radiative Heating of a Conventional and Aromatic Turbine Fuel

George A. Richards

U.S. Department of Energy, Morgantown Energy Technology Center
P.O. Box 880, Morgantown West Virginia, 26507-0880

Introduction

Infrared radiation has long been ignored in the calculation of droplet heating rates for spray flames. Because most hydrocarbon fuels are relatively transparent to infrared radiation, it has been routine to neglect radiative heating as compared to the very effective convective heating present in high-temperature environments. Indeed, in one of the very few detailed investigations of this problem, Berlad and Hibbard (1) found that radiative heating of fuel drops was negligible compared to convection. More recent work has considered the radiative heating of water drops (2). In this case as well, the radiative heating was small when compared to convection.

However, some experimental investigations have suggested that radiation seems to improve combustion efficiency (3) as well as increase flame speeds (4). Because spray combustion is often controlled by evaporation rates, these results suggest that radiation is somehow contributing to the evaporation process. This could be potentially useful for future fuels, which may be more aromatic with lower volatility than conventional hydrocarbon fuels. For example, Myers and Lefebvre (4) found that highly aromatic fuels had flame speeds which roughly cancelled the effects of fuel volatility. They suggest that increased flame radiance via aromatic contributions to soot could heat the fuel spray and diminish the importance of fuel volatility.

While it is certain that earlier conclusions are correct concerning the relative magnitudes of radiative versus convective heating (1,2), previous studies have not considered the situation where an ambient temperature spray approaches a luminous flame. Referring to Figure 1, a room temperature spray flows toward a stationary flame, or conversely, a flame propagates through a room temperature spray. In either case, there is no convective heating of the fuel drops until the drops enter the high-temperature flame front. However, radiation has opportunity to heat the fuel spray well ahead of the flame front. Furthermore, because the drops are bathed in room temperature air, any radiative heating they experience will be rapidly transferred to the surrounding air via convection. One can thus postulate that radiation will heat not just the drops, but the air as well. The magnitude of this effect is unknown. The analysis that follows is a first effort to quantify the radiative effect.

The radiative heating problem can be divided into three subproblems:

- Radiative energy absorbed by individual drops.
- The external radiative field.
- Conservation equations for droplet and air thermal energy.

Each of these subproblems has been treated in detail, but due to space limitations, only the first will be discussed in the current work. Subsequent publications will combine results from all three analyses.

Absorption of Radiation by a Single Drop

The absorption of radiation by small particle is covered in the texts by Van de Hulst (5) and Kerker (6). For the general problem, a laborious calculation from the Mie theory is needed to accurately compute the absorption for a single particle. However, under certain limitations, the spectral absorption cross section is given by an approximate formula:

$$Q_{abs,\lambda} = 1 + 2\exp(-4sn_2)/4sn_2 + 2[\exp(-4sn_2) - 1]/(4sn_2)^2 \quad (1)$$

where

$s = \pi D/\lambda$; the size parameter of a particle of diameter D subject to radiation at wavelength λ.

n_2 = the imaginary index of refraction at wavelength λ.

The limitations on Equation 1 are that

$$n - 1 \ll 1, \qquad n_2 \ll 1 \quad (2a,b)$$

where n is the index of refraction. The restriction 2b is easily met for fuels, but the restriction 2a is not precisely met because the index of refraction for most fuels is approximately 1.3. However, for simplicity, Equation 1 will be employed here, as in other investigations. Chan and Grolmes (7) successfully utilized Equation 1 to calculate radiative heating of water drops (n = 1.33) in a nuclear reactor cooling process. Plass (8) has compared the exact Mie solutions to Equation 1 for a range of values of n. From his results, it can be expected that Equation 1 will underestimate the absorption cross section when the restriction 2a is not met precisely. More precise evaluation can be obtained with the program due to Dave (9) or with the elegant ray-tracing procedure of Harpole (10). These complications are excluded in this initial investigation but could be easily adopted in a more comprehensive analysis.

Referring to Figure 2a, it is assumed that the spectral radiant intensity I_λ (W/m^2-str-μm) is uniform in the Θ coordinate but has a specified intensity distribution in ϕ. Note that the radiation direction is defined as positive when leaving the origin, so that the convention to define incident intensity is as shown in Figure 2b. The power absorbed by a drop of diameter D from radiation of wavelength λ is then

$$P_{abs,\lambda} = \frac{\pi}{4} D^2 Q_{abs,\lambda} \int_{4\pi} I_\lambda(\Omega)d\Omega \quad (3)$$

The integration is over the solid angle Ω. With the assumption that I_λ is independent of Θ and the substitution $\mu = \cos\phi$, Equation 3 reduces to

$$P_{abs,\lambda} = \frac{\pi}{4} D^2 Q_{abs,\lambda} \left[2\pi \int_{-1}^{1} I_\lambda(\mu)d\mu\right] \quad (4)$$

The term in brackets is the spectral irradiance which will be denoted G_λ:

$$G_\lambda = 2\pi \int_{-1}^{1} I_\lambda(\mu)d\mu \quad (5)$$

Furthermore, a spectral absorption coefficient is defined for drops of diameter D:

$$C_{abs,\lambda} = \frac{\pi}{4} D^2 Q_{abs,\lambda} \tag{6}$$

Combining Equations 3 through 5,

$$P_{abs,\lambda} = C_{abs,\lambda} G_\lambda \tag{7}$$

Because the drop is heated by the power absorbed across the spectrum, Equation 7 must be integrated over all wavelengths to calculate the total absorbed power:

$$P_{abs} = \int_0^\infty P_{abs,\lambda} d\lambda = \int_0^\infty C_{abs,\lambda} G_\lambda d\lambda \tag{8}$$

The total irradiance G is the integral of G_λ over the spectrum:

$$G = \int_0^\infty G_\lambda d\lambda \tag{9}$$

Then Equation 8 can be written

$$P_{abs} = G \left[\frac{\int_0^\infty C_{abs,\lambda} G_\lambda d\lambda}{\int_0^\infty G_\lambda d\lambda} \right] \tag{10}$$

The expression in brackets will be denoted the total absorption coefficient for drops of diameter D:

$$C_{abs} = \frac{\int_0^\infty C_{abs,\lambda} G_\lambda d\lambda}{\int_0^\infty G_\lambda d\lambda} \tag{11}$$

This reduces the expression for absorbed power to

$$P_{abs} = C_{abs} G \tag{12}$$

If the spectral nature of the incident intensity is given, then the value of C_{abs} can be computed from Equation 11. For a sooting, luminous flame, the spectral output along some direction μ will be approximated as proportional to a blackbody at the flame temperature T_f. That is,

$$I_\lambda(\mu) = k(\mu) I_{\lambda b}(T_f) \tag{13}$$

Here, $k(\mu)$ is an emissivity assumed independent of wavelength but may vary with μ. Because the intensity $I_{\lambda b}$ represents blackbody emission, $k(\mu)$ is obviously restrained to values between zero and one.

Substituting Equation 13 into 11, along with the definition of G_λ from Equation 5, the total absorption coefficient is

$$C_{abs} = \frac{\int_0^\infty C_{abs,\lambda}(2\pi \int_{-1}^{1} k(\mu) I_{\lambda b}(T_f) d\mu) d\lambda}{\int_0^\infty (2\pi \int_{-1}^{1} k(\mu) I_{\lambda b}(T_f) d\mu) d\lambda} \tag{14}$$

Noting that $I_{\lambda b}(T_f)$ does not depend on μ, this reduces to

$$C_{abs} = \frac{\int_0^\infty C_{abs,\lambda} I_{\lambda b}(T_f) d\lambda}{\int_0^\infty I_{\lambda b}(T_f) d\lambda} \tag{15}$$

From Equation 12, the power absorbed by a single drop thus depends upon evaluating the droplet absorption coefficient through Equation 15 and the external irradiance G. Evaluation of Equation 14 can be completed as long as the imaginary index of refraction n_2 is known (versus wavelength) for the drop medium. (Recall that $C_{abs,\lambda}$ depends upon $Q_{abs,\lambda}$, Equation 6, which in turn depends upon $n_2(\lambda)$ through Equation 1.) The value of n_2 may be obtained from transmission measurements of spectral intensity incident on a liquid sample of thickness t:

$$\frac{I_{\lambda t}}{I_{\lambda i}} = \exp(-K_\lambda t) \tag{16}$$

where $I_{\lambda t}$ and $I_{\lambda i}$ denote the transmitted and incident intensity at wavelength λ. The absorption constant K_λ is related to the imaginary index through the following relationship (8):

$$n_2(\lambda) = K_\lambda \frac{\lambda}{4\pi} \tag{17}$$

Transmission measurements as in Equation 16 abound in reference manuals for spectroscopic identification (12). However, such measurements are seldom used for quantitative absorption calculations because of variations in sample thickness, spectrometer response, etc. Despite these limitations, and because no explicit data on n_2 was otherwise found, spectra from several published sources will be used to calculate n_2. Published absorption spectra were corrected for window absorption by evaluating the transmission through the sample at a wavelength where the fuel was transparent. Integration is performed between 2.5 and 5.0 microns because hydrocarbons have no significant absorption bands below 2.5 microns (1) and most of the flame radiation is characterized by wavelengths shorter than 5 microns (13).

Figures 3 through 5 show the resulting calculation of C_{abs} as a function of drop size, at flame temperatures 1,200, 1,600 and 2,000°K. Each plot provides data on the fuels toluene (highly aromatic) and JP-4. The absorption spectra of these fuels were obtained from the reference indicated on the figures, and it is interesting to note that the results for toluene were calculated with spectral data obtained in 1956 (1) and also with more recent data (1985) from reference (9). Despite different test procedures, path lengths, etc., the results are essentially the same, providing confidence that the measured spectra are sufficiently accurate for the present calculations. Further inspection of the plots reveal that the fuel type has only a modest effect on C_{abs}. The modest differences between toluene and JP-4 are of minor importance compared to the order of magnitude variations observed with changes in the drop size. For practical purposes, these results indicate that the difference in radiative adsorption properties for conventional fuels (JP-4) and aromatic fuels (toluene), is surprisingly small. As was stated at the outset, the absorption coefficient can be used to evaluate the importance of radiative heating for the propagating flame where convective heating is absent until the drops enter the flame. Because of space limitations, these calculations will be included in a subsequent publication. However, the current results can be used to verify the established notion that droplet heating is dominated by convection in back-mixed flames, i.e., practical burners. If the drops exist in an environment with air temperature $T_\infty = T_f$ and black walls radiating at temperature T_f, then the ratio of convective to radiative heating is

$$\frac{\text{Radiative Heating}}{\text{Convective Heating}} = \frac{C_{abs}\, G}{h\pi D^2 (T_f - T_s)}$$

Here, h is the convection coefficient for a sphere in a quiescent environment and may be obtained from the standard Nusselt correlation (13), Nu = 2. Considering conditions which should exaggerate the above ratio (T_f = 2,000°K, D = 100 microns), the above ratio was found to be less than 0.02. The conclusion is that radiation can be ignored when droplet heating occurs by convection and radiation.

Summary

A simple procedure has been described to calculate a droplet absorption coefficient for infrared radiation. The coefficient can be calculated with reasonable accuracy from spectral absorption data on fuel samples. The coefficient was calculated for the fuels JP-4 and toluene. Results were relatively insensitive to fuel type but very dependent on the drop size. As expected, the results demonstrate that convection is more important than radiation in heating the drop. However, the present calculations are necessary to evaluate the radiative heating in situations where no convection operates, i.e., the propagating flame. This situation will be described in a subsequent paper.

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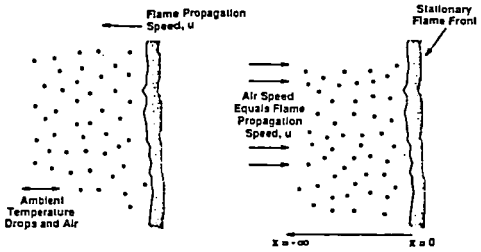


Figure 1

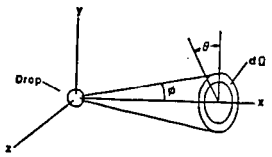
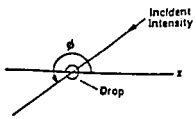


Figure 2a



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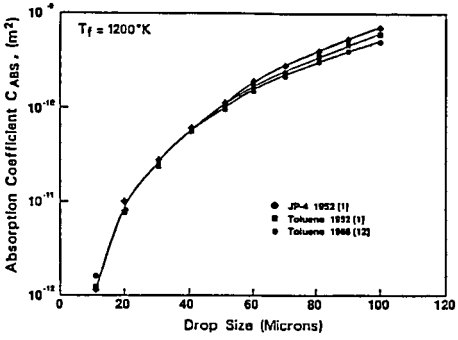

Figure 3

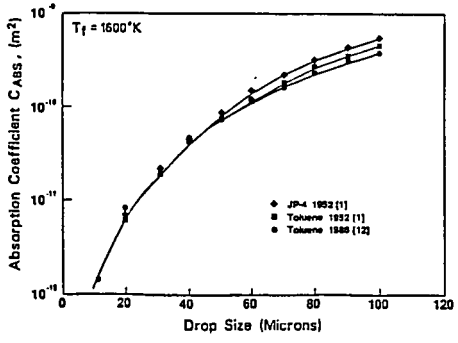

Figure 4

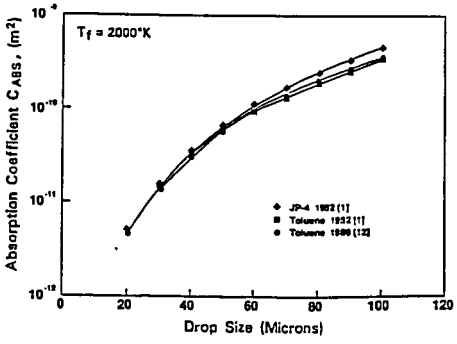

Figure 5